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Analysis and Prediction of Roughness of Face Milled Surfaces using CAD Model

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The condition for the designability and efficiency of the machining processes is that the part production process is chosen to meet the operational requirements based on the most accurate technological plans possible. One part of this is the planning of the required quality and roughness of the surfaces and achievement of the required values in the finishing. In this paper, a study on the predictability of surface roughness was performed using a CAD model based on theoretical roughness and validated by cutting experiments. The reported results show the effect of the feed rate change in face milling for two tools with different edge geometries in planes parallel to the feed direction.

Keywords: Face Milling, Surface Roughness, Theoretical Roughness, CAD Modelling of Roughness, Roughness Estimation

1 Introduction

The operation and lifetime of components incorporated into mechanical engineering products are significantly affected by the topography of the surfaces created by finishing machining. For this reason, the effect of factors influencing surface roughness in many or all machining processes is continuously and extensively researched. Several research results point to the importance of the chosen machining method [1, 2] and showing how the nature (defined tool edge or abrasive method) [3, 4] and the movement conditions of the tool and the workpiece create the surface of the parts. In addition, the effects of varying cutting data (cutting speed v_c, depth of cut a_p, feed rate f) are examined in all machining processes [5–9], as they influence the created topography to varying degrees, but always significantly. The reason for the interest in the topography of machined surfaces is that by changing the surface roughness, the friction between moving machine parts and the wear and corrosion resistance and creep strength of the parts can be influenced [10]. Therefore, the durability and lifetime of the components can be ensured with a surface that best suits the functional properties. When analysing the effect of influencing factors in finishing machining, the goal is not only to achieve the specified values, but also to estimate them in advance, or to choose a machining strategy for multi-axis machining based on, for example, the desired surface roughness and accuracy of the part [11]. Therefore, in addition to the analysis of roughness achievable with different machining, research aimed at estimating and planning roughness values is becoming more and more important [9, 12–14]. These analyses effectively contribute to the topography of the machined surfaces being as close as possible to the expected values.

1.1 Classification of modelling techniques with some examples

As previously discussed, researchers have long been involved in determining the expected value of surface roughness, and a number of procedures and modelling methods have been developed. Benardos and Vosniakos [15] classified the methods used to estimate surface roughness into four groups, as follows:

- Experimental methods: in these processes, correlations between cutting data and roughness are determined on the basis of data from cutting experiments.
- Designed experiments: whereas a large number of experiments are required to take into account each cutting data, so experimental design procedures such as response surface methodology (RSM) or Taguchi techniques for design of experiments (DoE) are often used to optimize the number of the needed experimental runs. These are differentiated from experimental methods by the fact that they constitute a systematic method concerning the planning of experiments, collection and analysis of data with near-optimum use of available resources.
- Analytical calculation or numerical methods: In these modelling procedures, the roughness values are determined by an exact or approximate mathematical description, starting from the geometric mapping of the tool and the workpiece, taking into account the kinematics and possibly other process characteristics.
- Artificial intelligence (AI) approaches: the most commonly used techniques are artificial neural network (ANN) models, genetic algorithms (GAs), fuzzy logic and expert systems.

Purely experimental methods are now rarely used, except possibly for special machining, where the primary goal is not to set up roughness models, e.g. [16, 17]. Designed experiments are much more common, and they are more frequently used, as is well summarized in [18]. Such a study was carried out in [19] to propose theoretical models from the measured roughness values to determine the expected roughness values of turned surfaces. The tests were designed using a factorial experimental design in which the response surface methodology (RSM) method was used; the machining procedure examined was turning, and the uncertainties of the process and measuring instruments were also considered.

Models based on analytical calculations are worth examining in a little more detail. A geometrical model was applied for the surface roughness prediction in face milling in [20] which is based on the re-creation of the tool trail left on the machined surface. The model was validated by experimental data obtained for high-speed milling of an aluminium alloy. The varied parameters were the cutting speed, feed per tooth, axial depth of cut and tool nose radius. An analytical surface roughness model was introduced in [21] for face milling that considers the profile and runout of each insert. The model was validated by face milling experiments where the feedrate was varied. The effect of the perpendicularity of the axis of the milling tool to the machined surface on the surface roughness was investigated in [22] in face milling. The investigated range was 90° ± 30´. Theoretical roughness was determined using analytical calculations. Mgherony et al. [23] investigated the effect of cutting parameters (feed and depth of cut) and tool nose radius on surface roughness in case of turning and milling. The measured data was compared with calculated theoretical values, which were obtained by analytical calculation of cusp height. A mathematical model was developed in [24] to predict the surface roughness in face milling using triangular inserts. Three cases were considered: when the tool marks consist of arcs, an arc and a line, and an arc and two lines. Every case has its own equation for the roughness profile calculation. Qu et al. [25] utilized parabolic and implicit approximation methods in closed-form solutions to estimate the Rt, Ra and Rq parameters. In the applied solution, the theoretical profile was assumed to consist of elliptical arcs. The runout of the inserts is obviously a very important factor when cutting with multi-point tools, as is shown in [26], where a numerical model was introduced for predicting the surface roughness considering the radial and axial runouts of the face milling tool. A random values generation algorithm was applied to determine the variation in roughness data according to the permissible runout of the inserts. A numerical model was introduced in [27] that allows the determination of roughness parameters in relation to cutting conditions, tool geometry, tool-workpiece materials and insert position errors in high-speed face milling operations.

As analytical calculation of surface roughness is often difficult, and "soft computing" methods are often used to determine it. These include various Artificial Intelligence (AI) methods, such as the gene expression programming method applied in [28]. A common feature of these methods is that real cutting experiments are used to teach the AI methods, which then become able to estimate the surface roughness expected when applying the given parameters. Cutting speed, feed and depth of cut were used as input data in [28] in the case of end milling. A hybrid algorithm was proposed in [29] to estimate the surface roughness in high-torque face milling: Genetic Algorithm (GA) was combined with artificial neural networks (ANNs). Several cutting experiments were conducted to train this complex system. A GA-based model was proposed in [30] for end milling where four independent variables – the spindle speed, feed rate, depth of cut and vibrations – were recorded during real cutting experiments to train the model. After that, the floating-point constants of the elaborated model were additionally optimized by a genetic algorithm to improve the accuracy of the model. Another important process parameter in face milling is the use of coolants and lubricants, as this also affects the roughness of the machined surface. Bruni et al. [31] investigated the effect of cooling and lubricating (CL) condition on surface roughness in finish face milling. Different CL strategies were applied: dry, wet and minimum quantity of lubricant (MQL). Multiple regression analysis (MRA) and ANN modelling methods were used during the investigations. Polynomial networks were used in [32] for the prediction of surface roughness in side-milling operations using the abductive modelling technique and based on the F-ratio to select their input variables. Correa et al. [33] used classifiers which were based on Bayesian networks to estimate the Ra parameter in high-speed machining. Their method used Naïve Bayes and TAN structures to develop empirical models for the roughness prediction using data obtained from real cutting processes. ANNs and an adaptive neuro-fuzzy inference system (ANFIS) are used in [34] to model the surface roughness in end-milling. The input parameters were the spindle speed, feed rate and depth of cut, and Ra was the only output parameter. First- and second- order mathematical models were combined with genetic algorithms to optimize the surface roughness for end milling in [35]. A regression model and ANNs were used in [36] to predict the roughness in face milling of aluminium alloy. The varied cutting parameters were the spindle speed *n*, feed rate *f* and depth of cut a_p.

A geometrical and a mechanical model were combined to construct a surface roughness prediction model for milling in [37]. The influence of various factors on the roughness were analysed: elastoplastic deformation, insert nose radius, tool orientation, cutting data, force, microhardness and material properties. The models were validated by cutting Ti6Al4V samples. A complex system was introduced in [38] to predict, monitor and control the surface roughness in high-torque milling. The system consists of three main components: off-line roughness prediction, online surface roughness monitoring and surface roughness control. For the prediction, ANNs were utilized. Perhaps only cyber-physical systems represent a greater degree of integration, such as the one presented in [39]. This work shows a system for chip monitoring via cutting chip size control in end milling. This is a two-level cyber-physical machining system: it connects the computing resources of a cloud machining platform to the machine tool via its smart sensor system. A smart optical sensor system was utilized to acquire and transfer in real time the values of the cutting chips sizes to the cloud level.

1.2 Surface roughness studies for face milling

This work deals with the analysis of the topography of surfaces created by face milling, which has been investigated by many researchers in different ways and for different purposes. Some of the results are introduced here. During the high-speed milling of hardened steel, the effect of cutting speed was analysed on roughness as well as on cutting force, tool wear and chip morphology [40]. It was found that the characteristics of the studied output parameters changed at a given speed, so as the speed was increased, the surface roughness decreased slightly below this critical value, and drastically increased above it. In [41], the authors also analysed the cutting force and roughness in the context of the cutting heat generated during the milling of hardened steel. It was observed that the thermal softening effect induced by higher heat resulted in a more stable cutting process with lower force, which in turn resulted in better surface quality. When using cooling-lubrication in different ways on aluminium alloy, it has been found that even at variable feed rates f_z, spindle speed *n* and depth of cut a_p, the change from dry machining to MQL technique led to about a 30% decrease in arithmetic mean roughness Ra, and switching to nanofluid produced a further 15% drop [8]. (The cutting parameters influencing roughness, in descending order, were: f_z, *n*, a_p.) The tool life and wear process and traces of a coated carbide tool were studied on stainless steel [10]. Surface roughness varied in close relation to flank wear. In the first wear phase (rapid initial wear), the average roughness Ra increased rapidly, then was stable before the appearance of notch wear, and then increased drastically.

There are improvements in face milling where the aim is to decrease the roughness of the machined surface. The results of an ultrasonic vibration-assisted milling are reported in [42], where the possibility of reducing roughness was investigated in theoretical topography and validated experimentally. It was found that increasing the cutting speed decreased the roughness, while increasing the vibration frequency increased it, and the effect of the latter was more significant. Also, the vibration assistance can reduce roughness, which is achieved at low speeds and proper vibration frequencies. A dynamic roughness monitoring system has also been developed to simulate the roughness of the surface to be cut [9]. Interaction studies made with a system based on the ANN method have shown that the feed rate has the greatest effect on the average roughness. The developed monitoring system can be used to reduce scrap and tool wear, making it practical and cost effective.

A frequently researched topic is the optimization of cutting data and possibly other cutting process parameters to minimize some output characteristics, such as surface roughness. Pimenov et al. performed the optimization for roughness, tool cost, power consumption, material removal rate (MRR) and tool life with feed f_z, cutting speed v_c and flank wear *VB* parameters [43]. Based on the observed non-linear functions of the input parameters for roughness, multi-objective optimization was performed using Grey relational analysis (GRA) to minimize cost and maximize productivity. Razfar et al. also optimized for minimum roughness with cutting data (v_c, f_z, a_p) using the harmony search (HS) algorithm, which was experimentally validated [14]. In addition, a predictive model was generated from their many experimental results using the ANN method, which contributed to finding optimal data. It was concluded that the combined application of the two methods is effective in finding the global mean roughness minimum (Ra^{min}) value. Apparently, the preliminary estimation of roughness can be utilized in industry, thus it is also a frequently researched topic. In support of this, some results will follow. In addition to the cutting data, the effect of cutting hardening has been studied on stainless steel [44], where it was found that this combination can be used to estimate Ra more accurately for hard-to-cut materials. By determining optimal (above) data, slowing of hardening, reduction of wear, reduction of energy consumption and improvement of surface quality were achieved. In addition to the cutting data, the vibrations generated during cutting were also considered by Wu and Lei [9] in creating the roughness predictive model using an ANN method. It was found that taking into account the vibration (in addition to the cutting data) can greatly increase the accuracy of the estimation, and based on Pearson correlation analysis, the Z-directional component of the (relative) vibrations of the tool-workpiece had a greater effect on roughness than the components in X or Y directions. In addition to the cutting data and vibration, Zhenyu et al. also measured the cutting force and the radial and axial runouts on the tool, from which they made a predictive model [45]. In the case of roughness, it was found that the runouts measured on the applied tool had a greater effect on the roughness than the feed rate. The predictive model is mainly recommended for multi-edged tool face milling.

This work deals with the analysis of the topography of surfaces created by face milling. The special feature of this material removal process is that it operates with a rotating tool, a variable chip cross section and intermittent chip removal. For this reason, changes in roughness on a machined surface are specific [46, 47], such as at different points, directions, or elements of a topography, not only in roughness values but also in the degree of surface inhomogeneity. The prediction of the topography and roughness of the surfaces produced by face milling is presented in many ways, e.g., based on the cutting edge geometry and cutting conditions [48], automatic estimation of roughness using artificial intelligence [49], or through developing a framework model for estimating the surface texture in milling operations [50]. Recent research has shown some methods for estimating 2D profile [9, 14] or 3D areal roughness [51, 52].

One approach is to estimate surface roughness using a theoretical profile generated by a CAD model, a method developed by Felhő [53]. The essence of this method is to determine the theoretical topography of the milled surface using a CAD model. The surface points are then transferred by an interface software to a professional surface topography analysis software that evaluates the values of the standard 2D and 3D roughness parameters calculated from the theoretical profile, which are therefore theoretical values. We have used this approach in our work to analyse the effect of cutting data [6], to investigate the effect of insert geometry [46] and to examine the roughness of the surfaces face milled with different tools having different edge geometries [54] and also the effect of the insert runout error [55].

In this paper, the effect of changes was examined in two parameters (cutting edge angle and feed rate) that fundamentally influence the theoretical profile of machined surfaces and the theoretical values of roughness in the direction of tool feed, in the plane designated by the tool axis and in two other parallel planes on the entry and exit sides of the tool edge. First, the effect of the insert geometry was analysed by examining the surfaces machined with a round and a rhombic insert, and then the effect of the feed on the circular insert (which produced surfaces with lower roughness values) was studied. The studies were basically focused on how to describe the theoretical roughness values according to the operating conditions. Since the theoretical value is essentially determined by the tool edge geometry and the feed measured in the tool reference plane, these was considered in the applied CAD model.

2 Materials and methods

The CAD model was created with the conditions chosen for the analyses. Using it, the theoretical milled surface was determined for each variation. Thus, for the two tool geometries and at five feed rates, the theoretical values of the 2D (arithmetical mean Ra and maximum height Rz) and 3D (arithmetical mean Sa and maximum height Sz) roughness parameters were determined in three measurement planes. Validation was performed by cutting experiments, during which the roughness of the milled surface was measured for both insert geometries (with fixed cutting data), at two feeds (at the circular insert) and in three measurement planes, and values of the above-mentioned parameters were investigated (Fig. 1). After analysing the real and theoretical roughness values, they were compared. Based on this, we evaluate how accurately expected roughness values were estimated based on the theoretical values without previous cutting experiments.

The surface roughness modelling was performed in the Autodesk Inventor CAD software. A parametric three-dimensional model was created which contains three main elements: the workpiece model (in this specific case, it is a simple block), the tool shape in the tool reference plane (as a 2D shape), and a sketch which contains the tool path. The tool shape is then guided along the specified tool path, which in face milling is a looped cycloid path lying in the assumed work plane [56]. By passing the tool along the entire machined length the model of the machined surface is formed. The theoretical machined surface created in this way must be exported, and then the desired roughness parameters can be determined by loading it into the surface roughness evaluation software.

Face milling experiments were performed on a Perfect Jet MCV-M8 vertical machining centre, where only one insert was mounted in the milling heads (Tab. 1). Here the geometry of the inserts is given with the following parameters: the primary cutting edge angle $\varkappa_r$, orthogonal rake angle γ_o, orthogonal clearance angle α_o, nose radius r_ε and size of the inscribed circle *iC*.

The rhombic insert was labelled IA (insert code:

R215.44-15T308M-WL) and the round insert was labelled IB (insert code: RCKT1204M0-PM). Workpiece material was normalized C45 steel (Rm = 580 MPa). The analysis conditions were symmetrical face milling, 58 mm wide workpiece surface. From the cutting data, the values of $v_c = 200$ *m.min*$^{-1}$, $a_e = 58$ *mm*, $a_p = 0.8$ *mm* were the same for all settings. The effect of the tool geometry was investigated at a fixed feed per revolution (0.4 mm.rev^{-1}). The effect of the feed (shown based on the results for the round insert) was analysed by modelling at feed rates of 0.1, 0.2, 0.3, 0.4 and 0.8 mm.rev^{-1} (Tab. 2). Two values (0.4 and 0.8 mm.rev^{-1}) were investigated during cutting and compared with theoretical data. We have chosen the round insert for the examination of the feed, because with the use of this insert better roughness can be achieved, so it is more expedient to use it for smoothing, to produce finer surfaces.

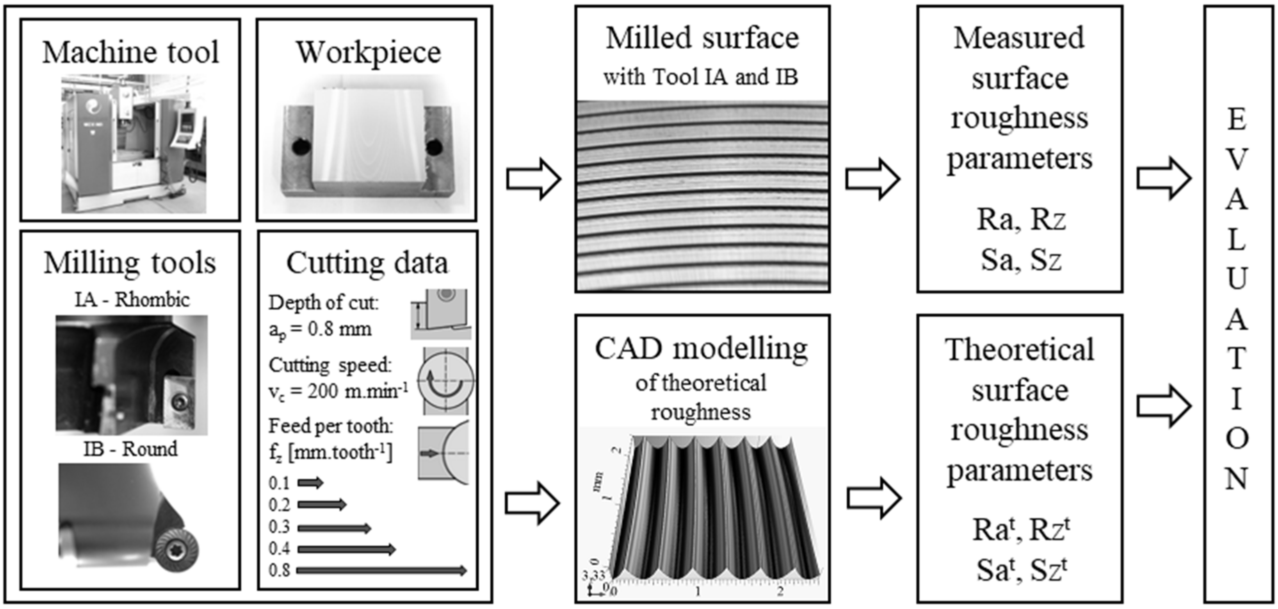


Fig. 1 *Process of the research work*

Tab. 1 *Cutting inserts*

Sign	Type	D_t [mm]	Details
IA	Rhombic	80	$\varkappa_r = 90°$; $\gamma_o = 0°$; $\alpha_o = 11°$; $r_\varepsilon = 0.8$ mm
IB	Round	68	iC = 12 mm; $\gamma_o = 0°$; $\alpha_o = 7°$

Tab. 2 *Cutting data*

No.	f_z [mm.rev^{-1}] IA	f_z [mm.rev^{-1}] IB	v_c [m.min^{-1}]	a_e [mm]	a_p [mm]
1		0.1			
2		0.2			
3	0.4	0.3	200	58	0.8
4		0.4			
5		0.8			

2D and 3D roughness measurements were performed on AltiSurf 520 roughness measuring equipment with a CL2 confocal chromatic probe. AltiMap Premium software was used for its evaluation. The roughness was examined in three measurement planes parallel to the feed direction: the first is in the line of symmetry, and in two equidistantly spaced parallel planes at a given distance from the line of symmetry (Fig. 2). The length of the 2D measurements was set in the areas defined by the ISO 4288 standard, and the areas in the 3D cases were 2.5×2.5 mm^2. 2D measurements were performed at three locations per measurement plane, and the results reported in this article are equal to their arithmetic mean.

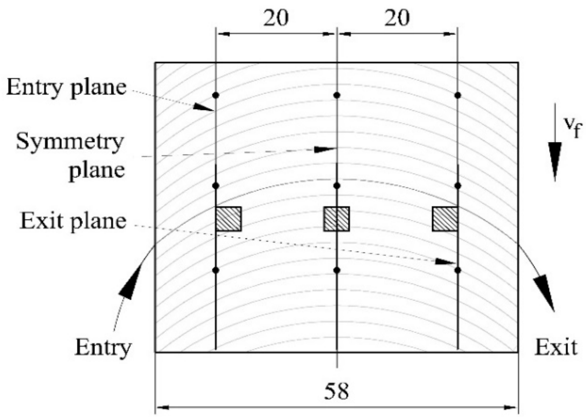


Fig. 2 *Positions of the measurements*

3 Results

For both tool geometries, the CAD models were constructed with the specified settings and the theoretical profiles were generated as previously described. The 2D result of this is shown in Fig. 3, while the 3D result is shown in Fig. 4. It can be seen that the surface has higher roughness in the symmetry plane, while in parallel planes equidistant from it, the same values are obtained on both sides.

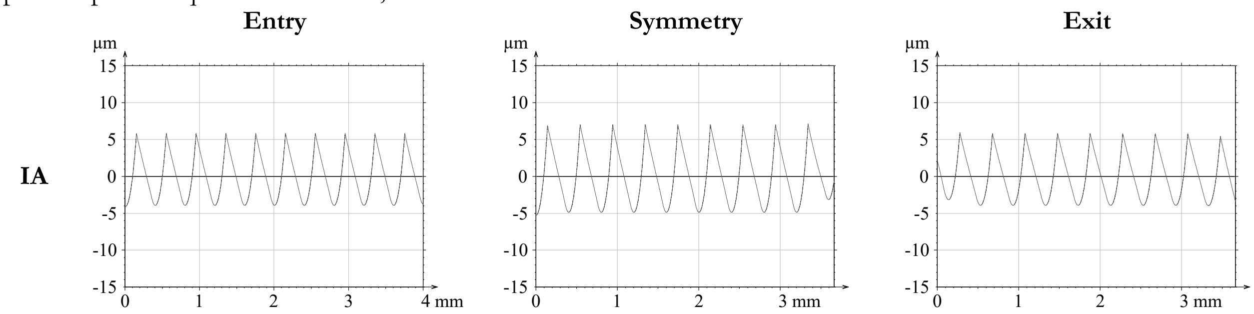


Fig. 3 *Theoretical roughness profile curves for f_z = 0.4 mm/rev with insert IA*

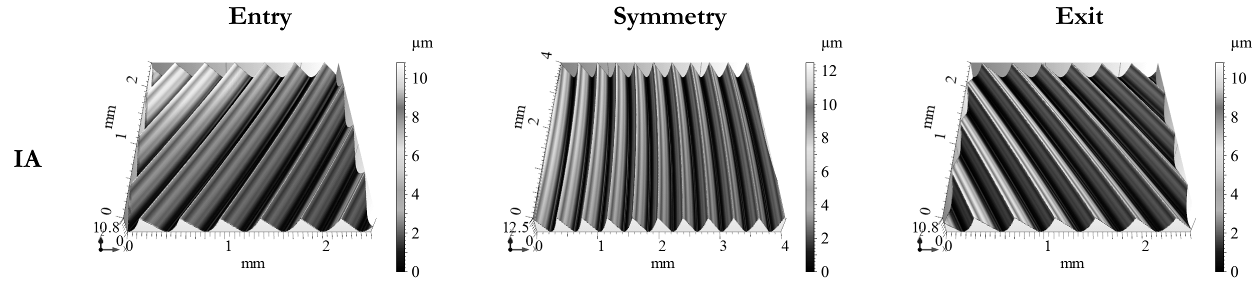


Fig. 4 *Theoretical surface topographies for f_z = 0.4 mm/rev with insert IA*

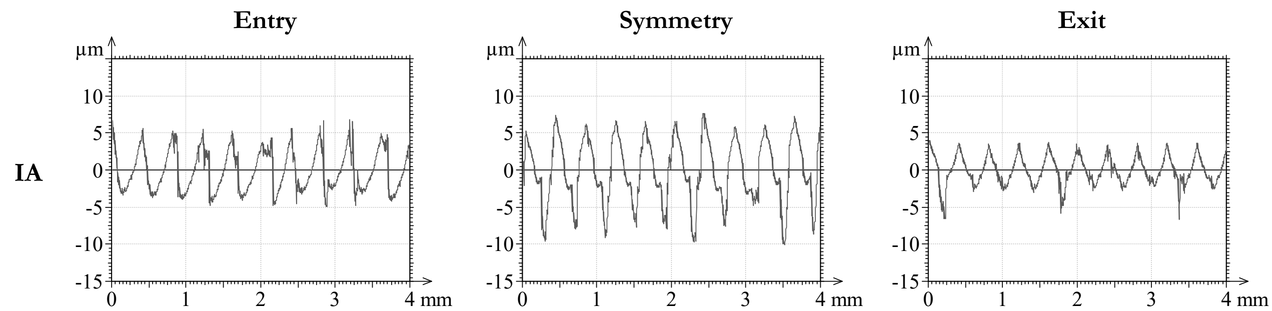


Fig. 5 *Roughness profile curves for f_z = 0.4 mm/rev with insert IA*

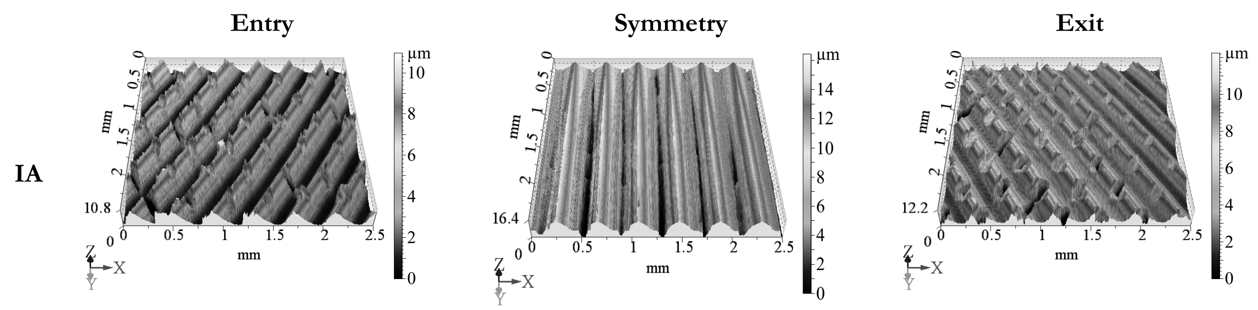


Fig. 6 *Surface topographies for f_z = 0.4 mm/rev with insert IA*

On the machined surfaces created with the same parameters, maximum roughness was also obtained in the middle plane and smaller values in the side planes; however, the magnitude of the roughness is different between them (Figs. 5,6). Moreover, marks of the tool edge appeared on the already machined surface in all the planes. This appears when the milling head fully runs along the milled surface and the tool is not tilted.

The investigation was proceeded in a similar manner when examining the effect of the round insert. The characteristics of the profile are the same as in the previous theoretical profile, but with the examined feed rate values, they have significantly smaller roughness (Figs. 7,8). Real roughness profiles recorded on milled surfaces also show this decrease (Figs. 9,10).

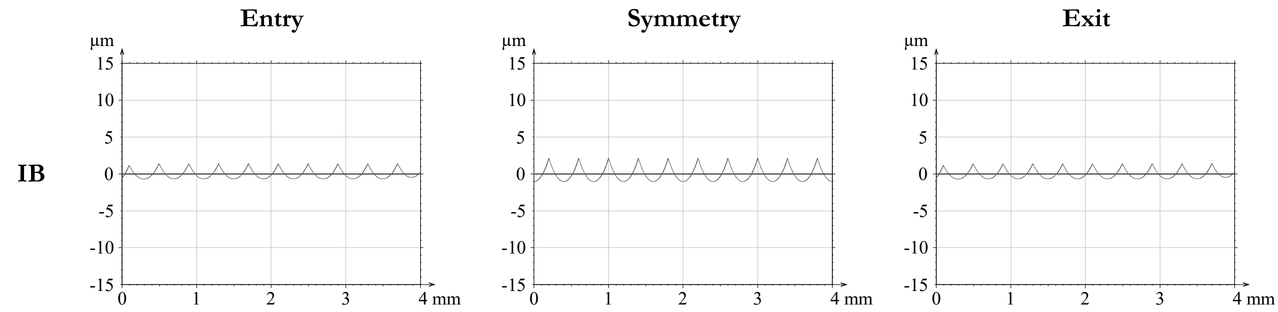


Fig. 7 *Theoretical roughness profile curves for f_z=0.4 mm/rev with insert IB*

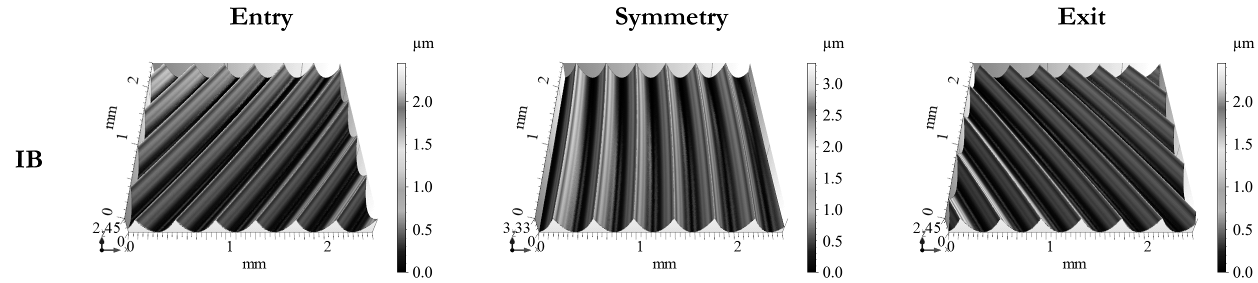


Fig. 8 *Theoretical surface topographies for f_z=0.4 mm/rev with insert IB*

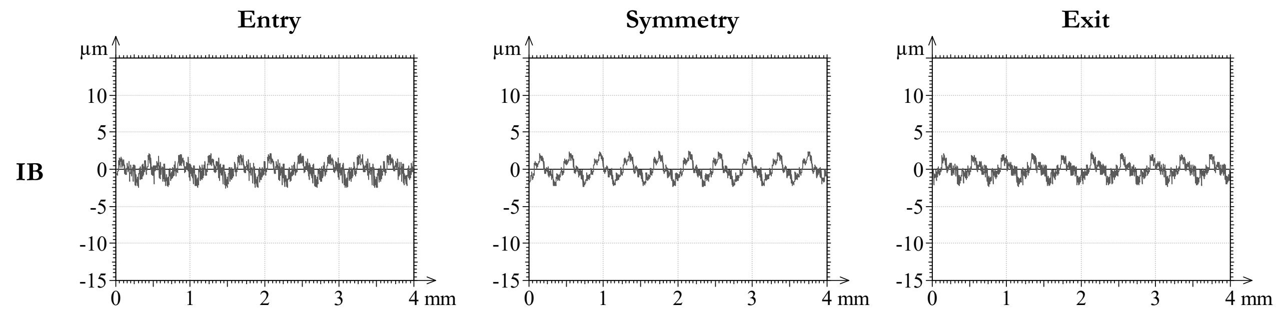


Fig. 9 *Roughness profile curves for f_z = 0.4 mm/rev with insert IB*

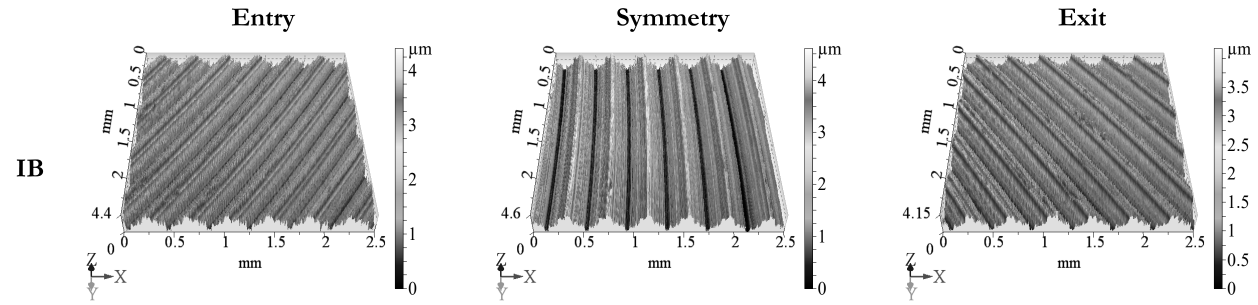


Fig. 10 *Surface topographies for f_z = 0.4 mm.rev^{-1} with insert IB*

During the examination, the roughness profile curves, topographies and the values of the analysed parameters were examined on the round insert (which gives lower roughness) for both the theoretical and real surfaces. Then, at the feed value of 0.4 mm, the theoretical and real roughness values were also measured with the rhombic insert, which served as a basis for comparison to analyse the effect of the insert geometries. The values given under the experimental conditions and the given feed series are presented to study the feed effect, as well as the theoretical surfaces were created for each case, from which the topography of the theoretical surface of the 0.8 mm.rev^{-1} feed rate (Figs. 11,12). Cutting experiments were also performed for the latter feed, and the profile diagrams and topographies of the milled surface are shown in Figs. 13 and 14.

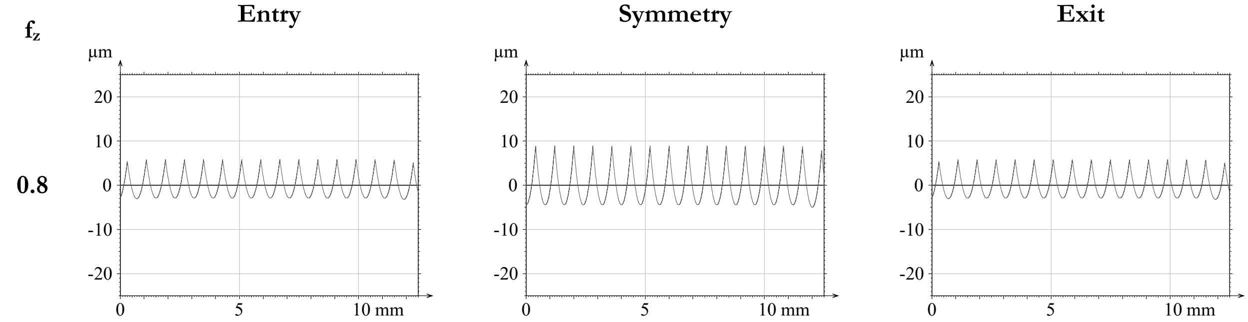


Fig. 11 *Theoretical roughness profile curves for f_z = 0.8 mm.rev^{-1} with insert IB*

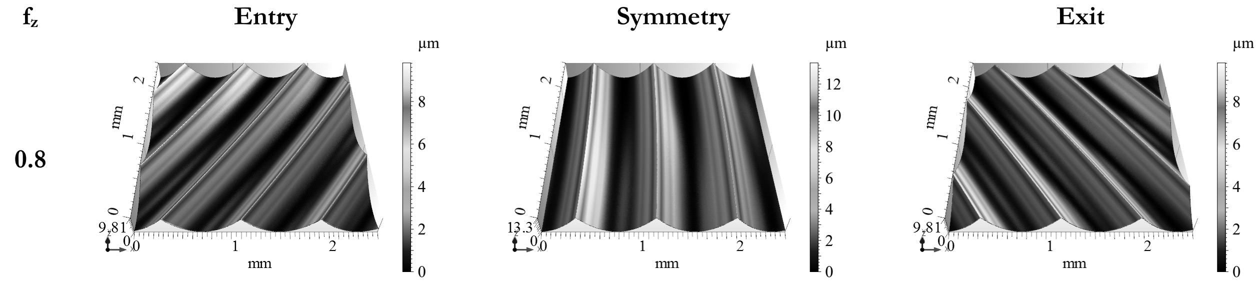


Fig. 12 *Theoretical surface topographies for f_z = 0.8 mm.rev^{-1} with insert IB*

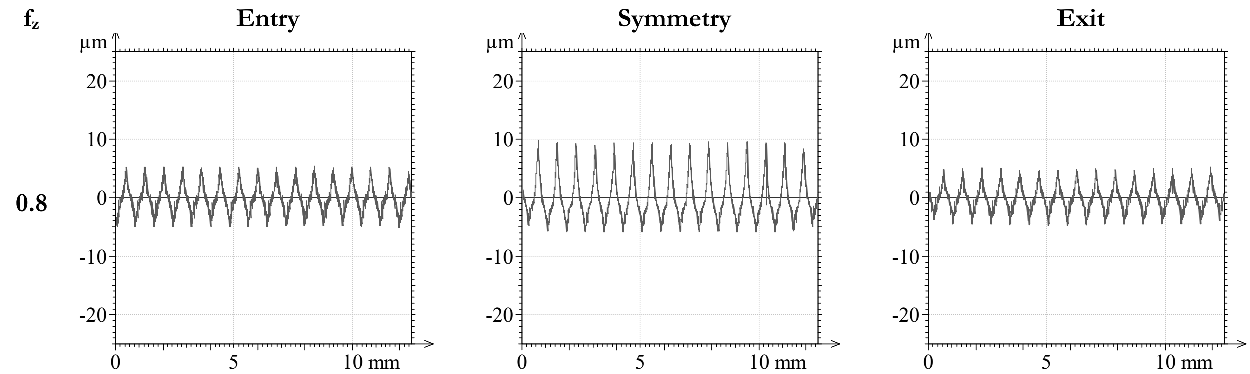


Fig. 13 *Real roughness profile curves for f_z = 0.8 mm.rev^{-1} with insert IB*

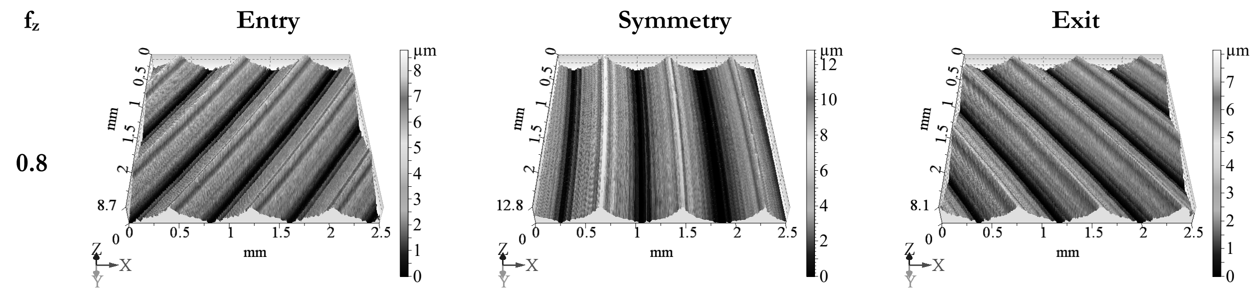


Fig. 14 *Real roughness profile curves for f_z = 0.8 mm.rev^{-1} with insert IB*

The roughness was measured for five different feeds on the selected circular insert (IB). For one of these selected (0.4 mm) feed values we compared the roughness with the rhombic insert (IA). The values of two 2D profile (Ra and Rz) and two 3D areal (Sa and Sz) parameters were calculated from the theoretical profiles, and the values measured on the machined surfaces were also given. The values for the rhombic insert are given in Tab. 3, while those for the round insert are given in Tab. 4 and Tab. 5. (note that the theoretical values of all standard 2D and 3D parameters can be calculated from the theoretical profile or topography).

Tab. 3 *Roughness values for insert IA*

f_z 0.4	Ra [µm]			Rz [µm]			Sa [µm]			Sz [µm]		
	Entry	Symm	Exit	Entry	Symm	Exit	Entry	Symm	Exit	Entry	Symm	Exit
Theo	2.620	3.170	2.620	9.750	11.850	9.750	2.860	3.380	2.860	10.800	12.500	10.800
Exp	2.239	3.591	1.534	10.822	15.263	8.609	2.548	3.383	2.289	11.820	16.535	13.212

Tab. 4 *Theoretical roughness values for insert IB*

Theo f_z	Ra [µm]			Rz [µm]			Sa [µm]			Sz [µm]		
	Entry	Symm	Exit	Entry	Symm	Exit	Entry	Symm	Exit	Entry	Symm	Exit
0.1	0.034	0.052	0.034	0.128	0.199	0.128	0.037	0.054	0.037	0.156	0.208	0.156
0.2	0.140	0.214	0.140	0.542	0.833	0.542	0.149	0.215	0.149	0.611	0.833	0.611
0.3	0.316	0.483	0.316	1.220	1.860	1.220	0.336	0.474	0.336	1.380	1.870	1.380
0.4	**0.526**	**0.803**	**0.526**	**2.070**	**3.170**	**2.070**	**0.596**	**0.846**	**0.596**	**2.450**	**3.330**	**2.450**
0.8	**2.220**	**3.400**	**2.220**	**8.720**	**13.300**	**8.720**	**2.390**	**3.420**	**2.390**	**9.810**	**13.300**	**9.810**

Tab. 5 *Experimental roughness values for insert IB*

Exp f_z	Ra [µm]			Rz [µm]			Sa [µm]			Sz [µm]		
	Entry	Symm	Exit	Entry	Symm	Exit	Entry	Symm	Exit	Entry	Symm	Exit
0.4	**0.807**	**0.949**	**0.750**	**4.626**	**4.731**	**4.467**	**0.885**	**0.999**	**0.828**	**4.523**	**4.907**	**4.431**
0.8	**1.704**	**2.971**	**1.703**	**9.822**	**15.375**	**9.902**	**1.911**	**2.723**	**1.746**	**8.716**	**12.442**	**7.956**

4 Evaluation and discussion

The experiments supported some of the characteristics of the roughness of face milled surfaces resulting from the motion conditions. On surfaces machined with sharp-edged tools – in most cases – the roughness values are measured in the direction of the feed rate or feed velocity, for example on cylindrical surfaces in the direction of the constituent. A theoretically identical value is obtained along any component during measuring, within narrow tolerances.

In face milling, it is known [57] that the machined surface roughness varies depending on the measurement location due to the kinetic conditions. This change can also be assumed in the direction of the feed rate if parallel planes at different distances from the symmetry plane defined by the path of the tool axis are examined. An exception is that planes equidistant from the symmetry plane show practically the same theoretical roughness values (Tab. 3 and Tab. 4). However, the profile diagrams and roughness values measured on the machined surface also show that in reality there may be differences even for planes at the same distance. These differences are not surprising. Due to the movement conditions of face milling, from the moment the tool edge enters the workpiece material until it exits, the conditions for the material removal are constantly changing. These changes appear in varying chip thickness, changes in the direction and magnitude of cutting edge movement, changes in cutting force acting on the edge, etc.

From the entry of the tool edge to the plane of symmetry (the plane including the feed direction and the axis of rotation of the milling tool), up-milling occurs, followed by a down-milling. Therefore, the topography of the surface was examined at each setting not only in the symmetry plane, but also in the other two planes taken at equal distances on either side of it.

Comparing the roughness of the surfaces milled with inserts with different edge geometries (Figs. 15,16), it can be stated that the values of roughness parameters in the symmetry plane are the highest in both modelled and measured values, in agreement with the profile diagrams. With lower roughness values in the parallel planes on the two sides, the theoretical values are the same in the two planes and in most cases the measured values are larger with insert IB and smaller with insert IA than the theoretical values. If the maximum permissible value for the surface is given in the part drawing as an expectation, the maximum roughness of the surface can be quite accurately predicted with the value calculated for the symmetry plane. A smoother surface can be produced by cutting with the round insert. The calculated (theoretical) values for insert IB are always smaller than the measured values.

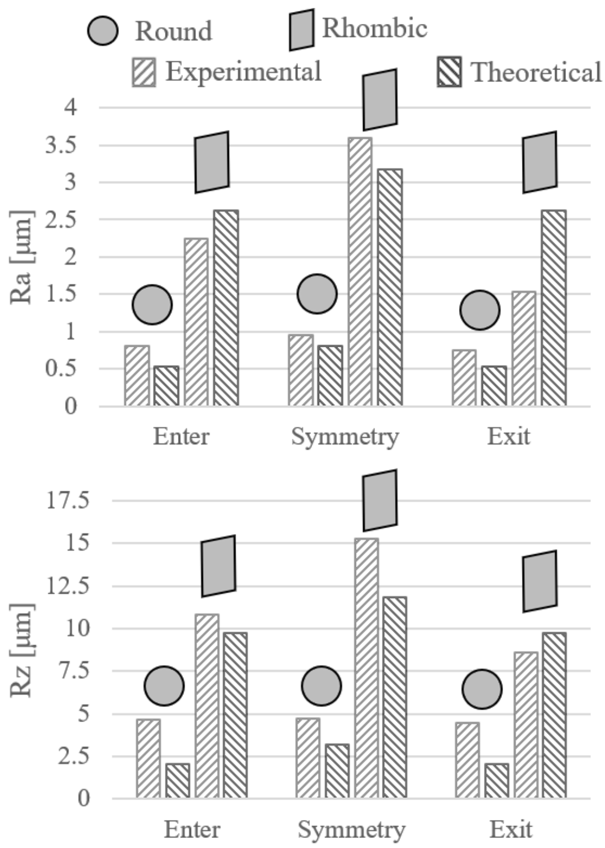


Fig. 15 *Changes in 2D roughness values at different edge geometries*

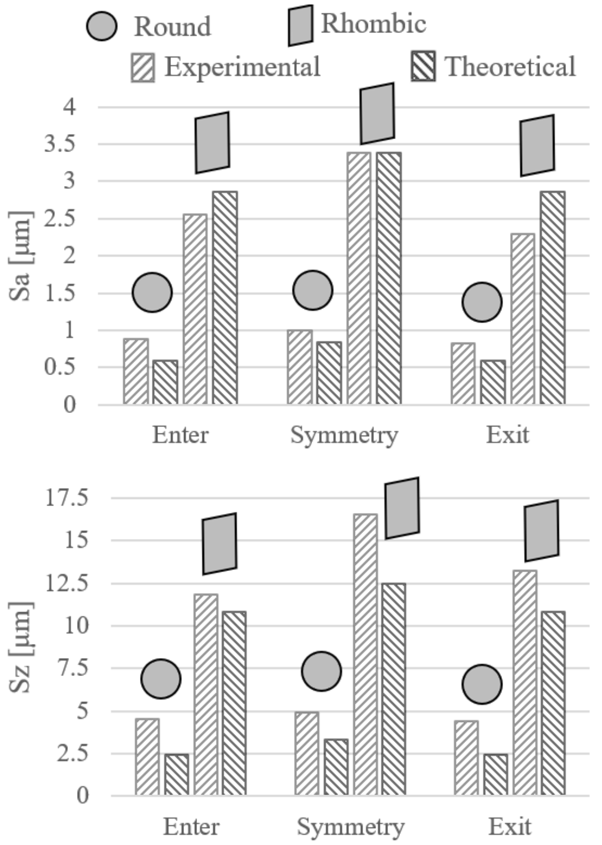


Fig. 16 *Changes in 3D roughness values at different edge geometries*

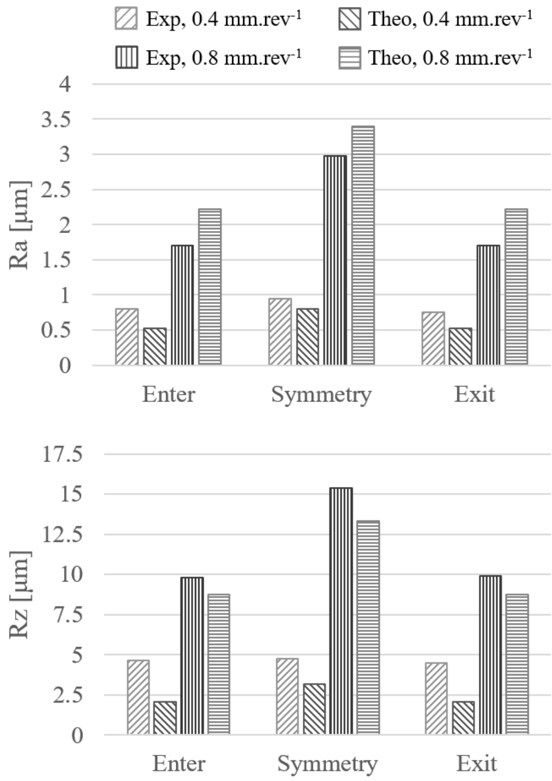


Fig. 17 *Effect of feed rate on 2D roughness*

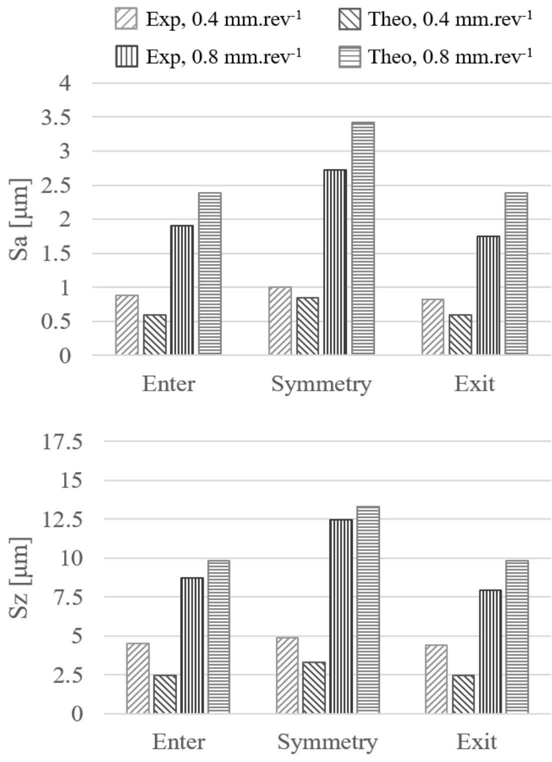


Fig. 18 *Effect of feed rate on 3D roughness*

Examining the effect of the feed change, it can be stated that the theoretical roughness values determined by modelling changed as expected (Tab. 4). As the feed rate increases, the values of all examined roughness parameters (theoretical, measured) increase (Figs. 17,18). At the same theoretical values on the entry and exit sides, Ra increased 65.3 times, Rz 68.1 times, Sa 64.6 times, and 62.9 times at Sz when the feed was increased eight-fold.

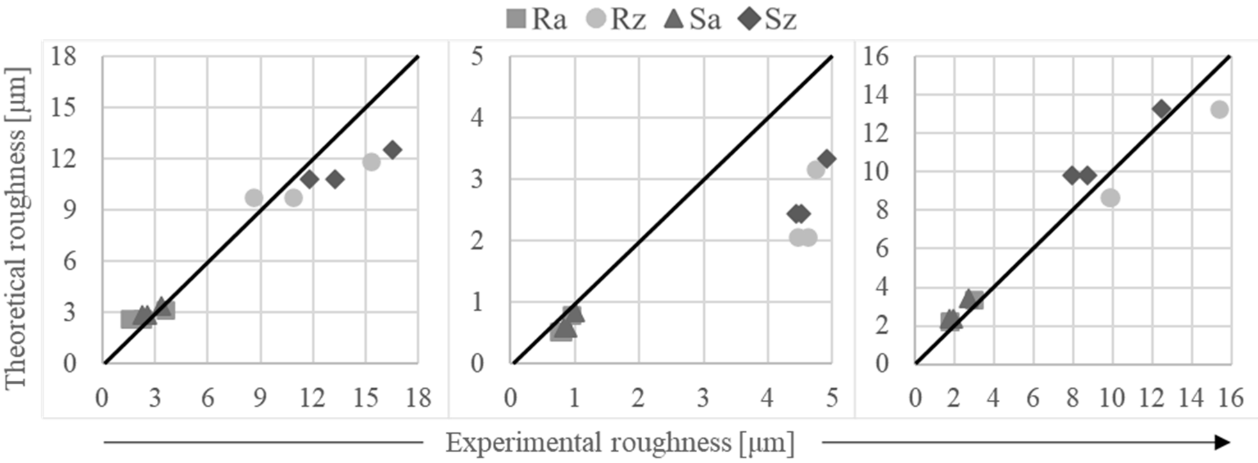
The results of the cutting experiments performed at 0.4 and 0.8 mm feeds were used for validation. The values of the roughness parameters are the largest in the plane of symmetry at both feeds on the machined surfaces. The values calculated by modelling are smaller at low feed and slightly higher at high feed on the milled surface compared to the theoretical values. At high feed, the values of the measured roughness parameters are almost the same on the two sides.

It should be noted here that in the planes parallel to the symmetry plane, the theoretical values are the same. With the increase of the feed rate, the theoretical values will increase. And with this, the accuracy of the estimation also increases. The theoretical and measured values of 2D and 3D roughness parameters change similarly.

5 Prognosis, estimation

An important question when examining surface topography is the extent to which the theoretical values determined in some way reflect the change in the actual (measured) roughness values. Therefore, the ratios of the experimental and theoretical 2D and 3D value pairs were analysed using diagrams (Fig. 19), showing the values measured in all three measurement planes of the surface machined with one setting.

It can be seen that most of the points show very good agreement in all three cases and are very close to the values that can be considered "ideal". The best fit (most accurate estimation) for roughness parameters was obtained with the average parameters (Ra, Sa), for the feed rate it was acquired with the higher feed values, and of the two insert geometries it was more accurate with the rhombic insert. The largest deviation occurred at the height roughness parameters (Rz, Sz) with the round insert and the low feed.



IA insert, f_z=0.4 mm.rev^{-1} ***IB insert, f_z=0.4 mm.rev^{-1}*** ***IB insert, f_z=0.8 mm.rev^{-1}***

Fig. 19 *Comparison of theoretical and experimental surface roughness values*

6 Conclusions

This paper has presented a study of the effect of the face milled surface roughness and the effect of two parameters influencing the theoretical geometric characteristics of the texture created by the tool edge: the feed rate and the tool edge geometry. Roughness analysis was performed with two edge geometries, at two feeds, and in three planes in feed direction. Using a CAD model, the theoretical surface was determined and from this the theoretical values of the 2D and 3D parameters were obtained. Validation of the results of the modelling was performed by cutting experiments. Comparative analysis and evaluation of the effect of the examined parameters was carried out. We found that under the examined conditions the expected roughness values can be accurately estimated based on the theoretical values.

We have further improved the capability of the developed CAD model and its suitability for machining with a rotary tool, which can be used to describe the change in the roughness on face milled surfaces. The change in roughness values for two tools with different geometries is shown in the symmetry plane and in two other parallel planes at the same distance from the first one. The round geometry was chosen as the base and the results from that tool were compared to the other edge geometry tool at two of the five feed rates set in this paper. The following conclusions were drawn.

- The maximum roughness value was always measured in the symmetry plane. In planes equidistant from it somewhat lower values were observed, which were identical at the two sides; however, the profile diagrams and roughness values measured in these planes on the machined surface showed differences, due to the changing material removal conditions.

- Experimental roughness values were larger with the round insert and smaller with the rhombic insert in most cases compared to the theoretical values. This is due to the fact that the larger the radius is, the harder it is to cut out its shape from the metal. The larger radius also modifies the force distribution, and thus the dynamical effects (e.g. vibrations) will be significantly larger [58].
- Despite this, a smoother surface can be produced by cutting with the round insert.
- When the feed was increased eight-fold the studied roughness parameters had an increase in values of about 63-68 times.
- Comparing the ratios of the experimental and theoretical roughness value pairs, the most accurate estimation was obtained with the average parameters (Ra, Sa), with the higher feed value, and with the rhombic insert. The largest deviation occurred at the height roughness parameters (Rz, Sz) with the round insert and the small feed.

Thanks to the general structure of the CAD model, it is possible to determine the theoretical roughness values for practically any cutting kinematics and any tool-material pairing. There are many opportunities for further development of the introduced method. Because three-dimensional surface points are available to us using CAD modelling, the vibrations, tool wear and other confounding factors can be taken into account relatively easily when calculating the theoretical values.

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